Status of the US Virtual Laboratory for Technology

Phil Ferguson
for the VLT members

TOFE 2016
August 25, 2016

What is the VLT?

- Formed in 1998 to provide a single entity with central leadership for the US technology program
  - Provide advocacy for the technology program
  - Provide representation among the fusion program leaders
  - Build consensus within the program
  - Program management, guidance, and direction remains with FES
- Largely dormant since 2013 (Milora retirement)
- New director named in May 2016
- Currently 15 institutions
  - 8 universities, 1 private company, 6 national labs
  - ~8% of US non-ITER budget

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VLT Research Areas

- Plasma Chamber Technologies
  - Magnet systems
  - Heating and current drive
  - Plasma fueling, ELM pacing, Disruption mitigation
  - Vacuum systems
- Fusion Materials Research
  - Plasma-materials interactions
  - Structural materials
- Harnessing fusion power
  - Integrated design studies
  - Power handling
  - Fusion Safety
  - Fuel cycle research
  - Blanket technology

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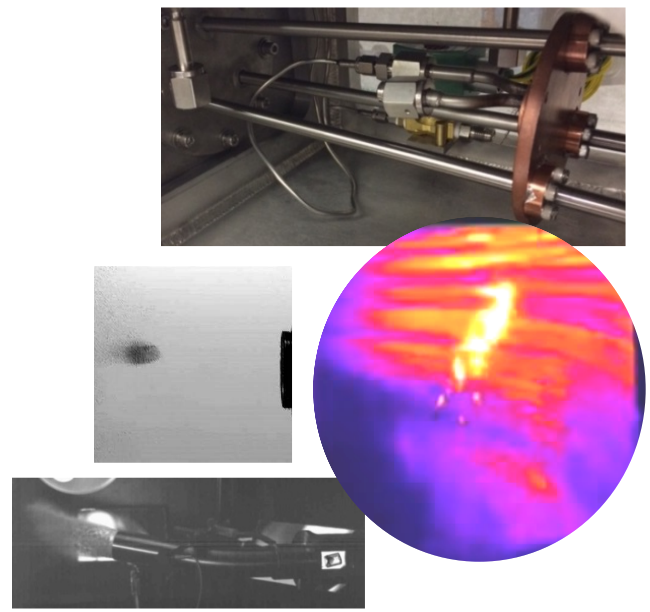
ORNL’s Fueling Technology Team is addressing three major challenges for fusion energy

- **Provide deuterium/tritium fuel mix to central core of burning plasma**
  - Continuous and reliable frozen D/T pellet being developed for ITER burning plasma operation
  - ORNL Fueling Technology/USITER team has extended pellet and injection technology to > 30 Hz — Progressing towards improving D/T mass flow and duration by a factor of 1000
- **Limit erosion of wall materials from large transient heat loads – “ELMs”**
  - ORNL Fueling Technology/USITER/DIII-D team has developed plasma edge pellet injection techniques that reduce ELM intensity > 12 X on DIII-D
- **Developing disruption mitigation technologies that have the goals of:**
  - Reducing heat loads to ITER wall materials by 10 X
  - Reducing electromagnetic structural forces 2-3 X
  - Reducing runaway electron beam intensity and energy by at least a factor of 10



S. Meitner, S. Combs, L. Baylor

Oak Ridge National Laboratory

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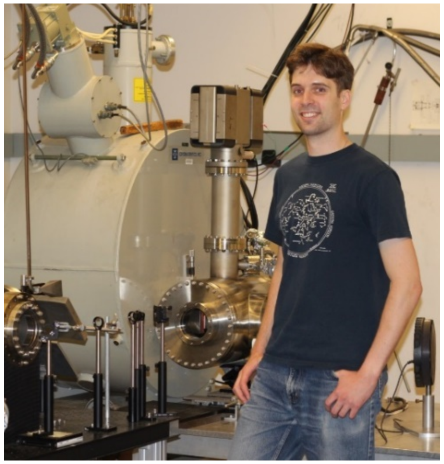
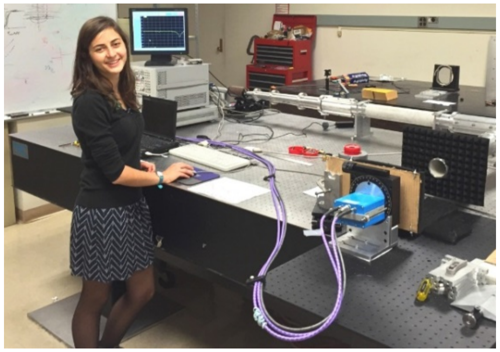
MIT's ECH Technology Team is improving output & efficiency for today's current and future machines

- Experimental and theoretical research on megawatt gyrotrons for ECH and ECCD to:
  - Increase gyrotron efficiency
  - Increase output mode purity
  - Compare diode and triode electron guns
  - Improve understanding of gyrotron mode competition
  - Support DIII-D ECH program at 110 GHz and gyrotron development in industry (CPI) at 110 to 170 GHz
- Experimental and theoretical research on low loss transmission lines for gyrotron power
  - Theoretical analysis of losses in transmission line components such as miter bends, gaps, sliding joints, and polarizers
  - Lab tests of loss in components at low microwave power
  - Supports US ECH program and US ITER IPO
- International Collaborations with Japan, Europe, ITER



MIT Gyrotron Lab



MIT Microwave Test Lab

Principal Investigator: Richard Temkin, MIT

"Experimental Results for a Pulsed 110 GHz / 124.5 GHz Megawatt Gyrotron," D. S. Tax et al. IEEE PS (2014)

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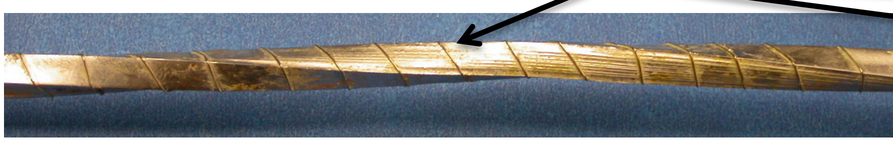
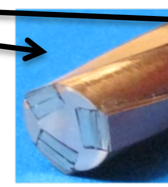
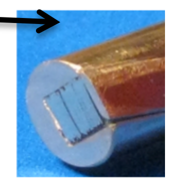
MIT's Magnet Technology Team is looking for innovations

- Basic research in superconductor and magnet technology towards understanding present state-of-the-art superconductors and magnet systems, with the ultimate goal of advancing these technologies for use in *future magnetic confinement fusion devices*.
- R&D is presently focused on magnet technology likely to be used for future devices beyond ITER especially including development of ***High Temperature Superconductors (HTS)*** for high current, high field, fusion magnet applications.
  - Peak field at magnet 18 – 22 T
  - Cooled to 20 K
- International collaboration with magnet programs in EU and Japan.

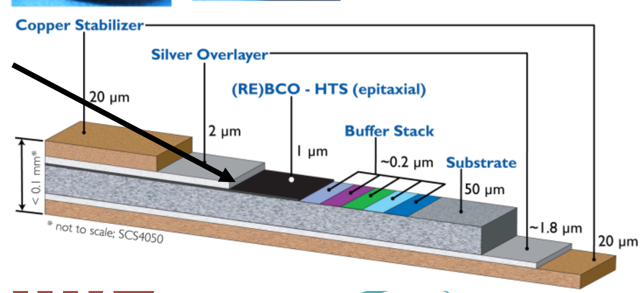
High Current, High Field HTS Twisted Stack Tape Cable (TSTC)







REBCO HTS Tape



Principal Investigator: Joseph V. Minervini, MIT

"Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path," D. G. Whyte, J. Minervini, B. LaBombard, E. Marmar, L. Bromberg, M. Greenwald, J. Fusion Energ (2016) 35: 41.

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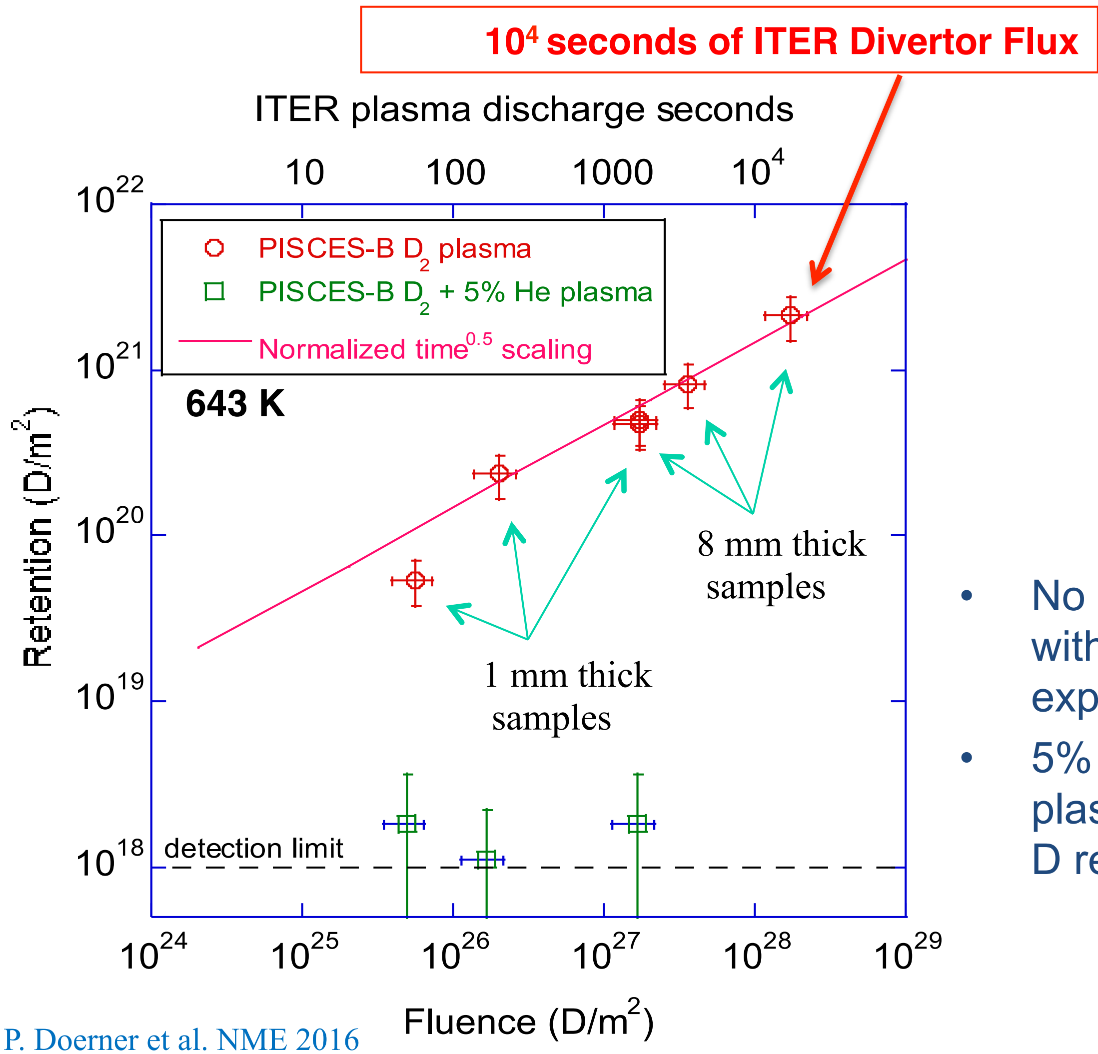
PISCES-B operated continuously for 31 hours to generate data at a world-record fluence of 2×10^{28} m^{-2}



- No saturation in D retention in W with high-fluence deuterium plasma exposure
- 5% He^+ flux during deuterium plasma exposure drastically reduces D retention in W at 643 K

R. P. Doerner et al. NME 2016
http//dx.doi.org/10.1016/j.nme.2016.04.008.

UCSD University of California San Diego

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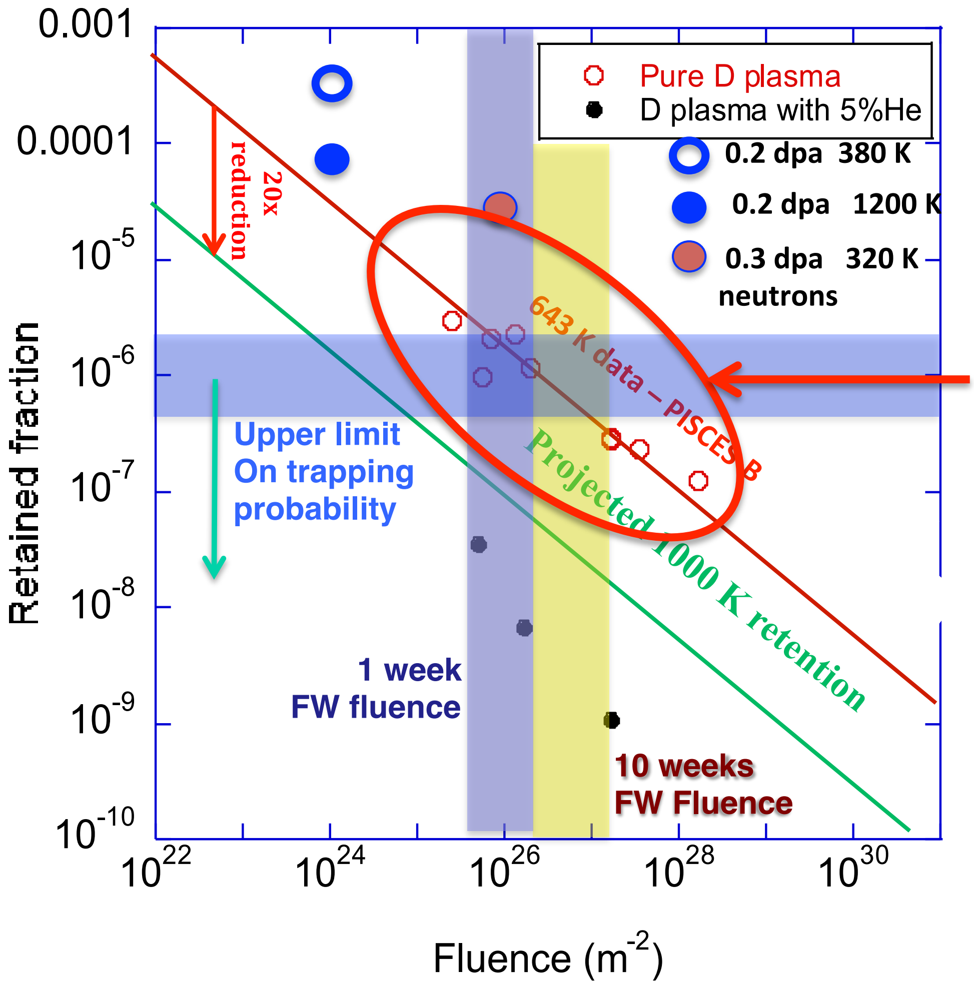
Tritium self-sufficiency requires a retained fraction of less than ~10^{-6}, which has been achieved at high fluence in undamaged samples

Tynan, PSI, Rome, 2016 submitted



Motivates
Higher Plasma Fluence
Ion Beam Damaged
&
Neutron Irradiated
Sample
Experiments

UCSD
University of California San Diego

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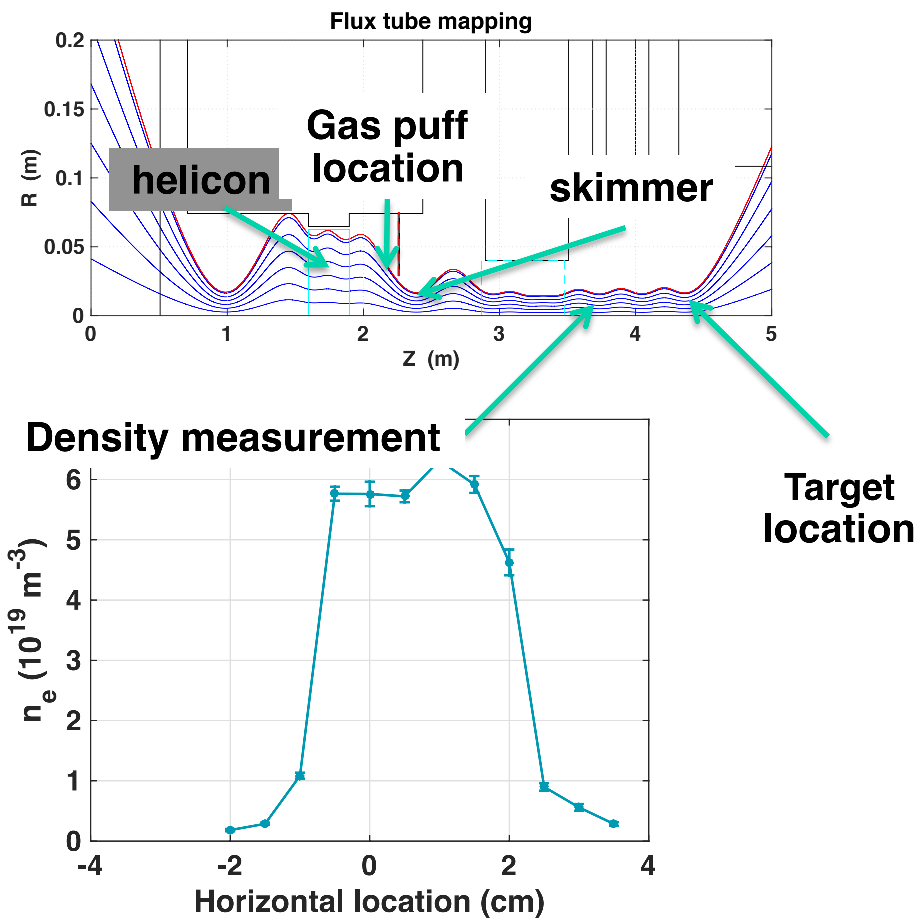
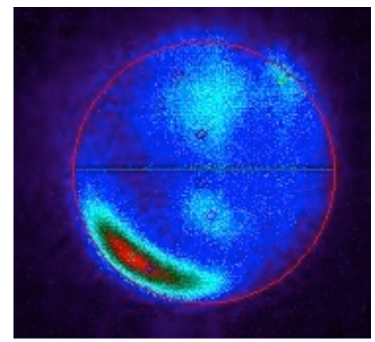
Proto-MPEX achieves record deuterium density with helicon source

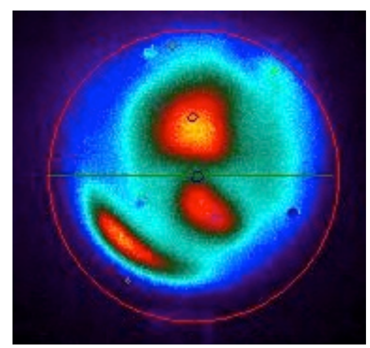
- High density helicon mode achieved with optimized fueling scheme and efficient excitation of helicon mode



IR data from backside of target



Before helicon mode transition



After helicon mode transition

J. Rapp, R. Goulding, M. Showers

OAK RIDGE National Laboratory

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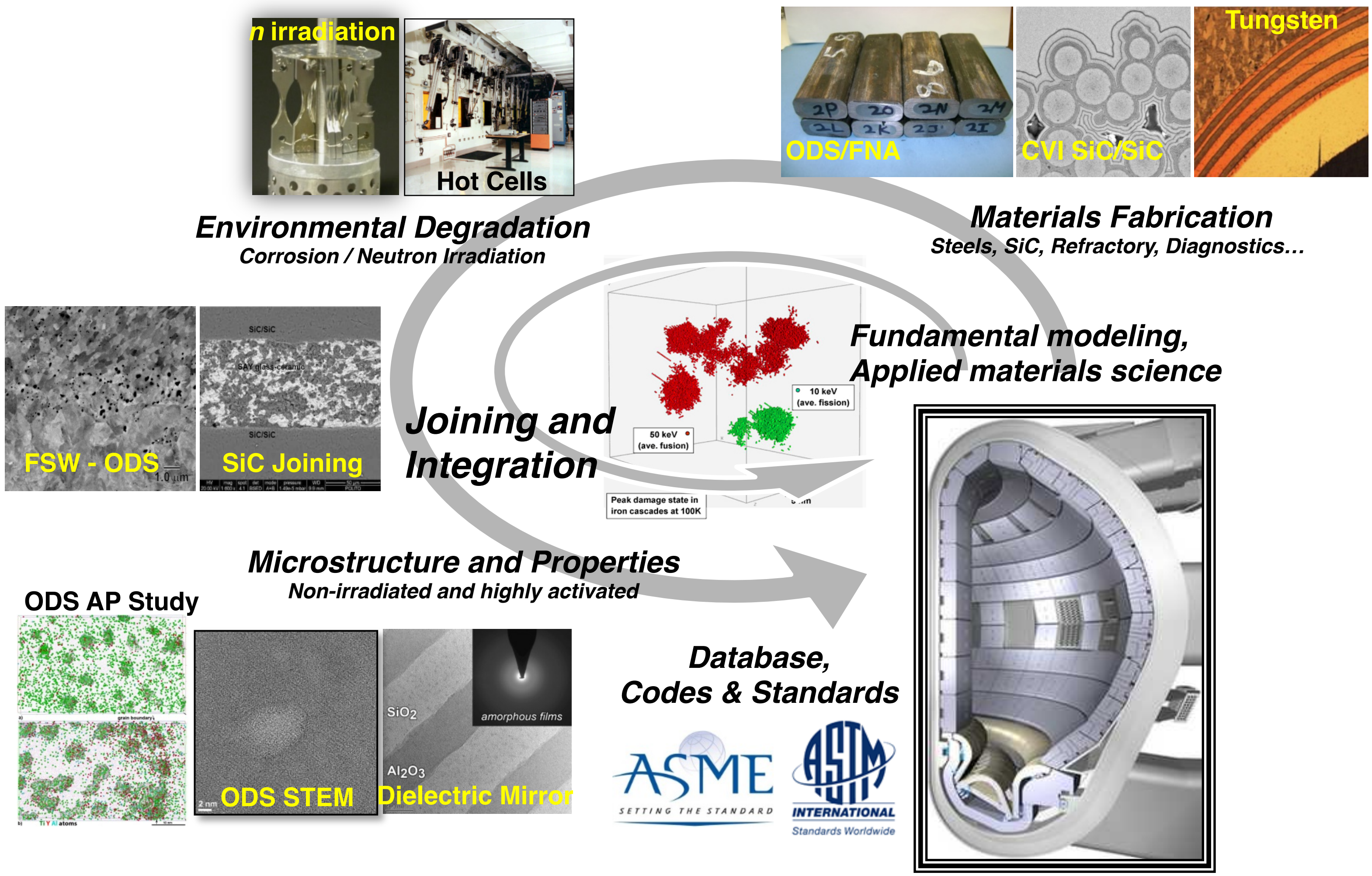
ORNL Fusion Materials Program covers basic materials properties to deployed solutions



Y. Katoh et al.

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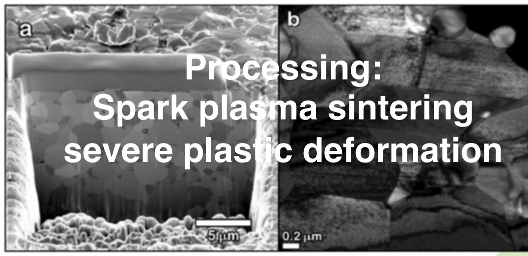
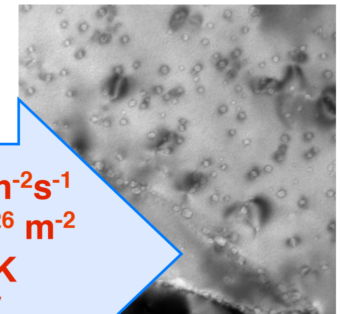
Process-property-performance relationships studied in well-diagnosed *in-situ* experiments at Illinois

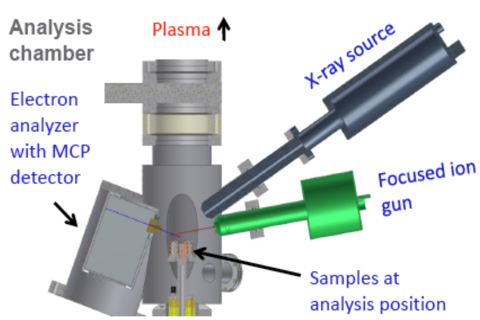


Multi-scale irradiation on extreme-refined grained W

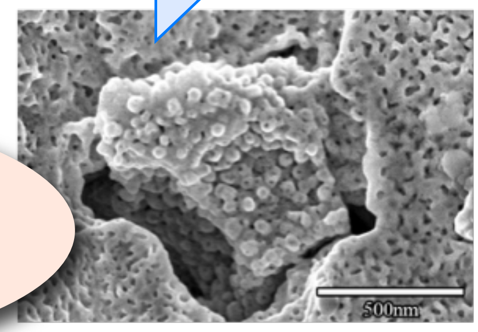
Irradiation behavior of hot lithium-based coatings

Fluxes: 10^{18}-10^{24} $m^{-2}s^{-1}$
Fluence ~ 10^{18}-10^{26} m^{-2}
T ~ RT up to 1200K
E ~ 10 eV to 2-keV





In-situ PMI diagnostics: MAPP in NSTX-U



ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

J.P. Allain, F. Bedoya, A. Neff, E. Lang, A. Kapat and H. Schamis

C.H. Skinner, F. Bedoya, F. Scotti, et al. *Advances in boronization on NSTX- Upgrade*, Submitted to J. Nucl. Mater. And Energy (2016).

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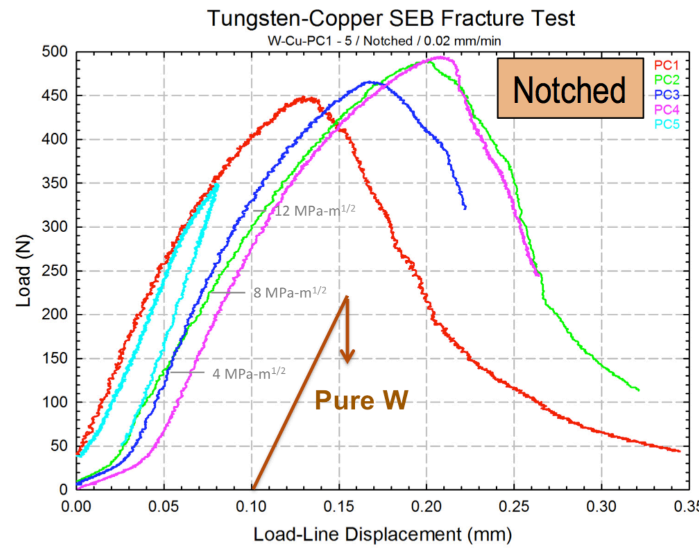
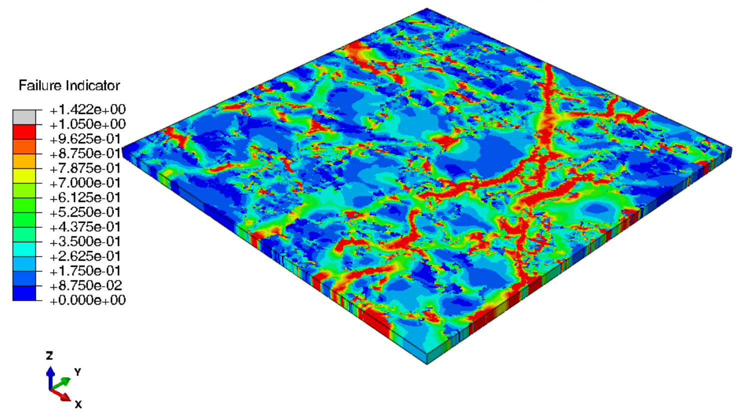
Ductile Phase Toughening of Tungsten may improve fracture resistance for fusion applications

- Development of tungsten-based composites with greatly improved fracture resistance is underway
  - Capitalizes on extensive work on toughening of brittle ceramics and intermetallic phase composites
- Notched three-point bend fracture experiments were performed on a **W-Cu composite** and a **W-Ni-Fe alloy**
- Initial results show that ductile phases contribute significantly to increasing fracture resistance
- Sophisticated crack-bridging models are being developed to treat crack growth in brittle matrix composites
  - Leads to the design of high-strength, high-ductility plasma facing components





UCSB

Pacific Northwest NATIONAL LABORATORY

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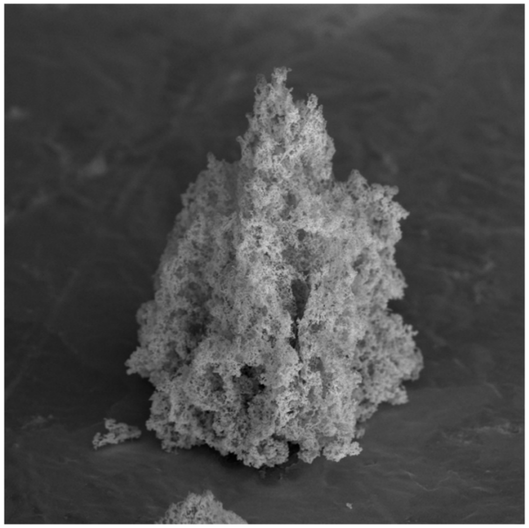
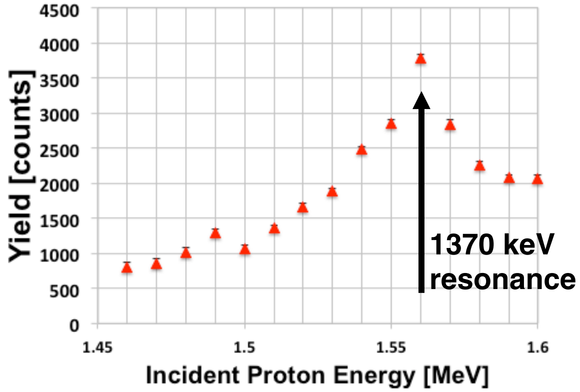
MIT Fusion Materials Researchers are studying fuzz, erosion, and HTS radiation damage

- New regime of tungsten nano-tendril growth, Nano-tendril Bundles (NTB)
  - NTB form when there is an ion energy distribution of He ions.
  - Provides insights into growth mechanisms
- Neutron damage experiments on HTS tapes for high-field magnets
  - Comparison study between neutron damage (MIT reactor) and ion irradiation (DANTE)
  - Neutron fluence will be 2x higher than previous studies on HTS
- Implanted depth markers for measurements of net erosion/deposition of bulk materials in tokamaks.
  - Implanted F depth markers and measured depth via nuclear resonance profiling
  - Implanted tiles will be deployed in NSTX-U and EAST





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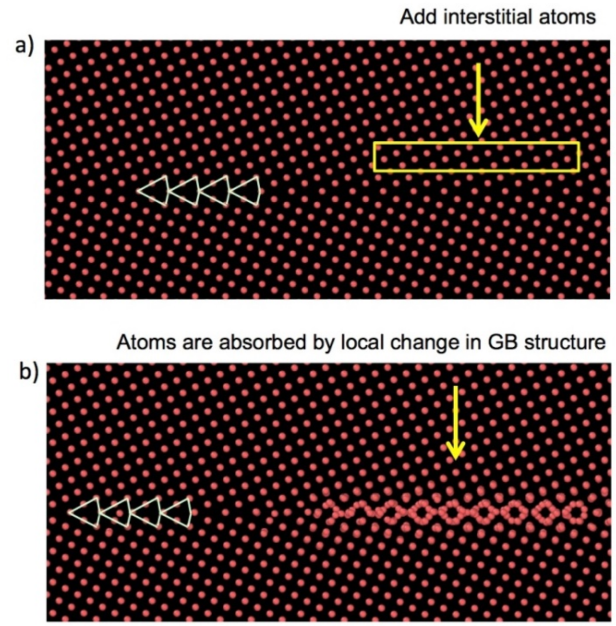
Graham Wright et al.

LLNL is using advanced materials modeling to bring understanding to tungsten behavior

- Recrystallization limits the operating temperature for tungsten in divertor and first-wall applications
- Molecular dynamics and multiscale modeling techniques are being used in collaboration with the Marian group at UCLA to develop a predictive model of recrystallization
- Recently high temperature phase transformations in tungsten grain boundaries have been predicted for the first time
  - Grain boundary phase transformations have a strong influence on their mobility, affecting recrystallization.

Robert E. Rudd and Tim Frolov (LLNL FWP SCW0458)

Grain Boundary Transformation



T. Frolov and R. E. Rudd, "Structure and Mobilities of Tungsten Grain Boundaries Calculated From Atomistic Simulations," 2016 Fusion Materials Semiannual Report.

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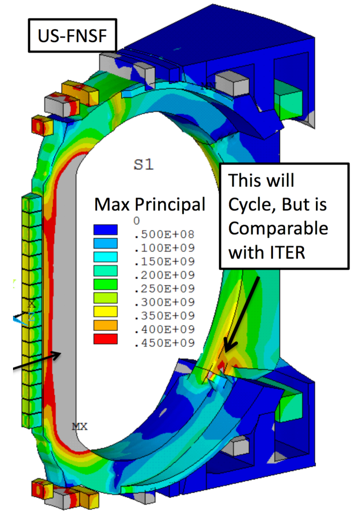
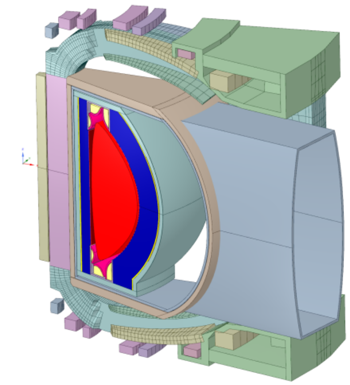
PPPL-led multi-institutional activity is exploring the FNSF as the first fusion nuclear break-in device

Key questions:

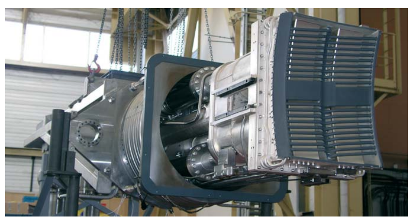
- What must it accomplish?
- How to measure its progress to a power plant?
- What is the FNSF program to accomplish its mission?
- What are the critical pre-FNSF R&D activities?

TF/PF Analysis





RF launcher assessment

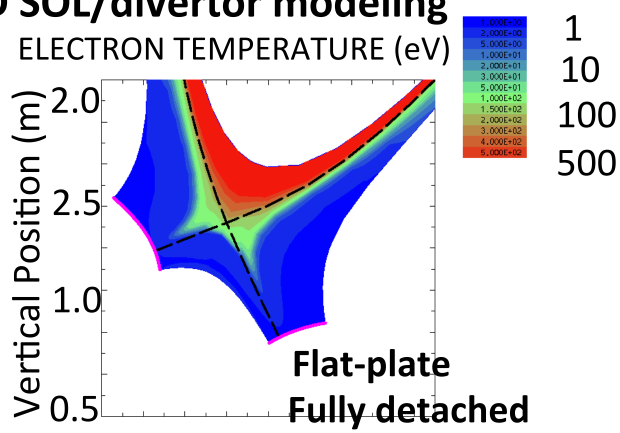


PSFC

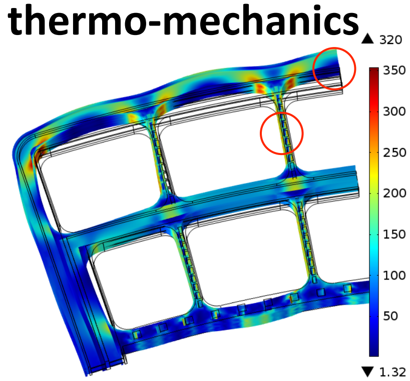
Idaho National Laboratory

PPPL PRINCETON PLASMA PHYSICS LABORATORY

2D SOL/divertor modeling



Multi-physics thermo-mechanics



(off-normal condition)

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

UCLA

UC San Diego

OAK RIDGE National Laboratory

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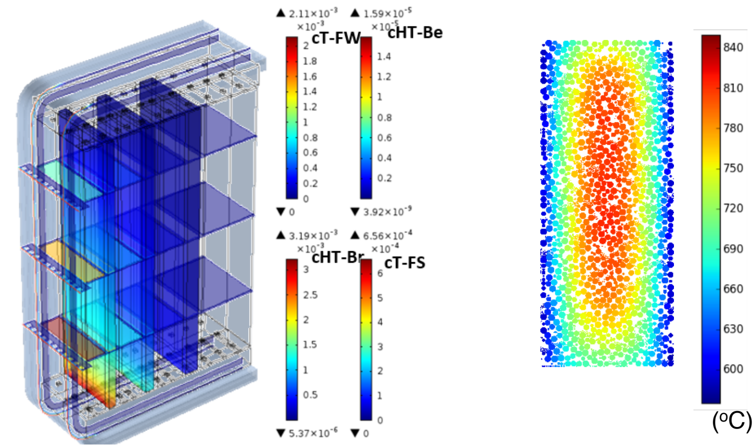
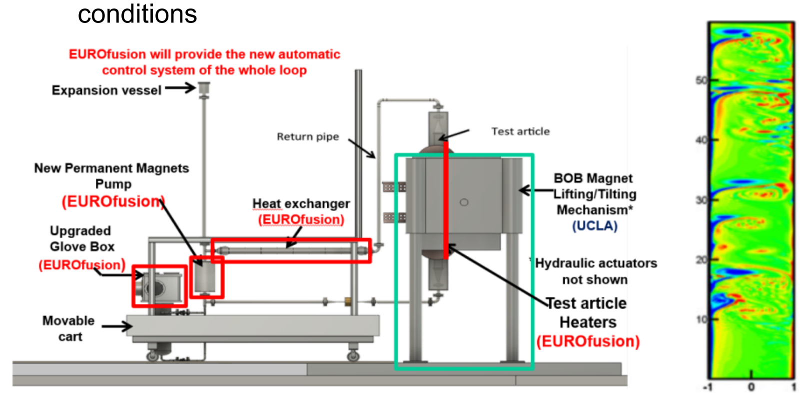
UCLA Fusion Science & Technology Center leads the US blanket effort

Focused R&D in niche areas of US scientific strength, capability, & leadership on FNS and Materials Interactions/Blanket/Tritium

- Liquid Metal MHD Thermofluids and Materials Interaction (with EUROfusion)
- Ceramic Breeder/Multiplier Material System Thermomechanics
- Tritium Transport, Permeation, and Fuel Cycle Dynamic Modeling
- Blanket Design & Analysis
- Selected functional materials properties, behavior, and fabrication (with SBIR, international collaborations, & structural materials program, INL)



Multi-physics modeling of tritium transport in 3D for ITER HCCR TBM submodule (left) (tritium concentration mol/m^3 is shown); (right) Helium purge gas regulated pebble temperatures under pebble bed/structural thermomechanical interaction with fault conditions



Recent discoveries at UCLA of the importance of mixed-convection flows (right) motivated us to quickly upgrade the unique MaPLE LM MHD facility (left) to address multiple effects in LM blankets

A. Ying, H. Zhang, B. Merrill, M. Ahn, Advancement in tritium transport simulations for solid breeding blanket system, presented at SFNT-12, *Fusion Eng. Des.*, 2016. http://dx.doi.org/10.1016/j.fusengdes.2015.11.040

J. T. Van Lew, A. Ying, and M. A. Abdou, Numerical study on influences of bed resettling, breeding zone orientation, and purge gas on temperatures in solid breeders, *Fusion Eng. Des.*, 2016.

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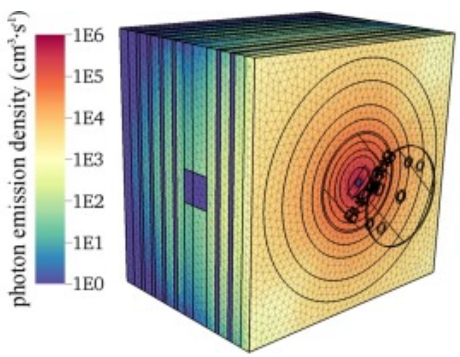
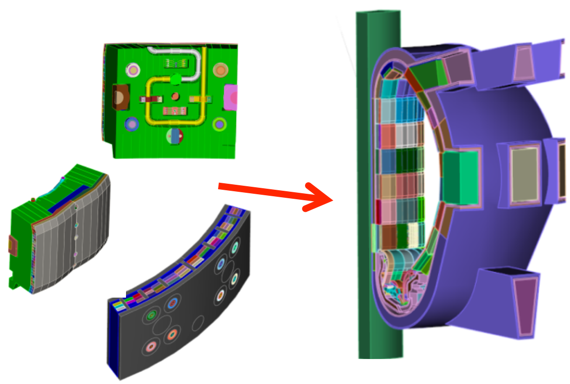
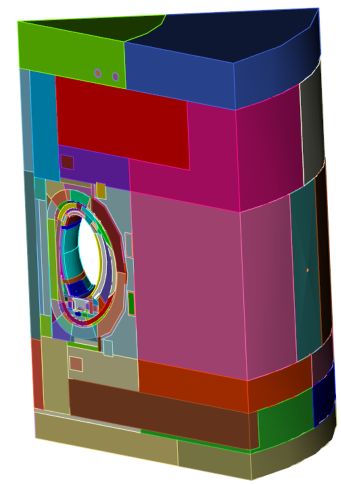
Wisconsin-led neutronics analyses are a key component of the systems studies and material evaluation



Total photon emission density distributions at the 1.22 h decay time in the FNG ITER shutdown dose rate benchmark



Detailed 3-D ITER neutronics model used for nuclear data benchmarking with DAG-MCNP5



3-D JET CAD model for DAG-MCNP5

E.D. Biondo, A. Davis, P.P. H. Wilson, “Shutdown Dose Rate Analysis with CAD Geometry, Cartesian/tetrahedral Mesh and Advanced Variance Reduction”, Fusion Eng. & Design, Vol. 106, P. 77-84, May 2016.

T.D. Bohm, M.E. Sawan, “The Impact of Updated Cross Section Libraries on ITER Neutronics Calculations”, Fusion Science and Technology, vol. 68, issue 2, P. 331-335, Sep. 2015.

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

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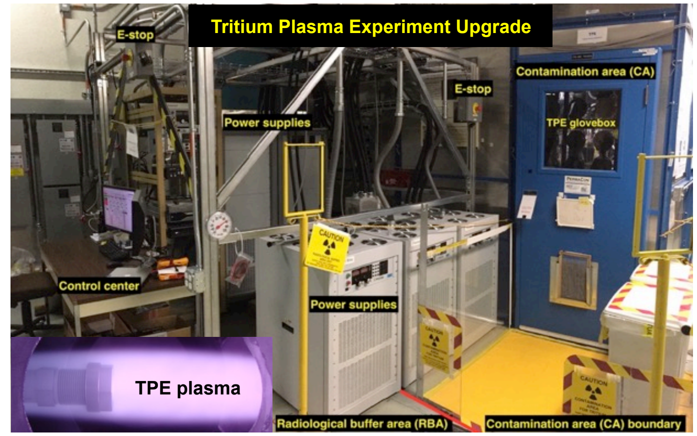
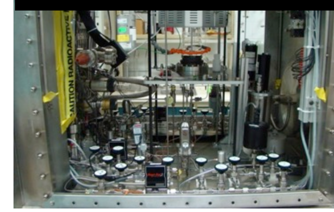
INL has led the Fusion Safety Program since 1979

- **FSP's Mission**: Assist the fusion community in developing the inherent safety and environmental potential of fusion power:
  - Developing fusion licensing data and analysis tools
  - Operating Safety and Tritium Applied Research (STAR) facility to advance fusion nuclear and tritium sciences
  - Participating in national and international design studies
  - Assisting the US and international fusion community in licensing activities and guidance in operational safety



- **Recent research highlights:**
  - In Nov. 2015, the Tritium Plasma Experiment (TPE) achieved its first D plasma using the new control center outside of the CA after significant 3-year upgrade
  - New system to measure T permeability in a wide range (12 orders of magnitude) in T_2 partial pressure was developed for fusion and fission materials
  - MELCOR for fusion and Tritium Migration Analysis Program (TMAP) codes were merged as a single comprehensive safety analysis tool for fusion reactors

Tritium Gas Absorption Permeation



Tritium Source System & Tritium Exhaust Processing

M. Shimada, C.N. Taylor *et.al.*, *Fus. Eng. and Des.,* 109-111 (2016) 1077
R.J. Pawelko, M. Shimada *et.al.*, , *Fus. Eng. and Des.*, 102 (2016) 8.
B.J. Merrill, P.W. Humrickhouse, and M. Shimada, *Fus. Eng. and Des.,* 109-111 (2016) 970

INL Idaho National Laboratory

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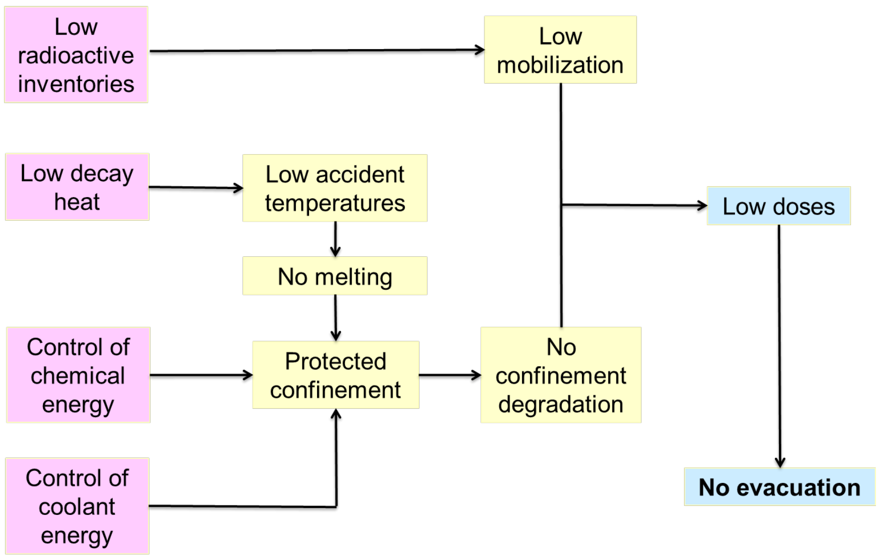
LLNL also plays a key role in fusion safety, environment, and tritium research

- Collaborating with Idaho National Laboratory (INL) on fundamental safety and tritium research
  - Leading accident identification studies
  - Supporting INL in safety analysis and tritium
- Supporting FNSF team in remote maintenance and hot cell aspects, and materials safety requirements
- Promoting and facilitating national and international information exchange and collaboration on topics of safety and T fuel cycle

Goal of accident analysis is to show fusion safety objectives are met



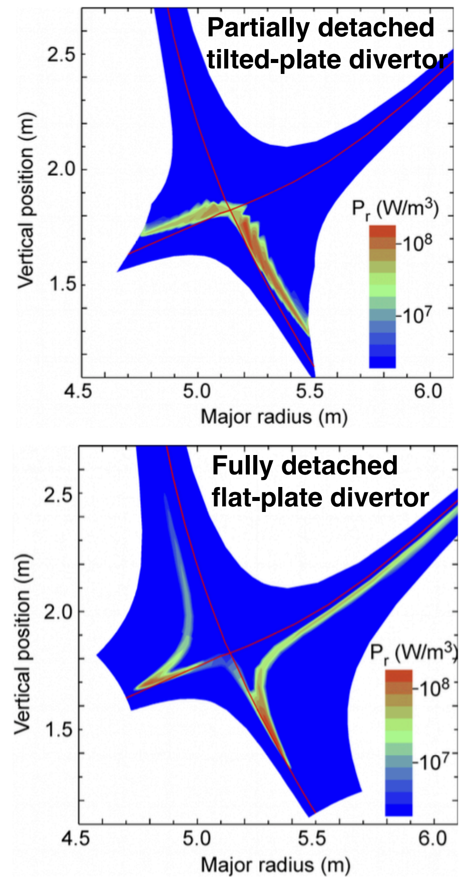
S. Reyes et al., “Safety Considerations for Fusion Energy: From Experimental Facilities to Fusion Nuclear Science and Beyond,” IAEA Fusion Safety Meeting paper (2016).

P. Humrickhouse, S. Reyes, B. Merrill, “Safety in the Fusion Nuclear Science Facility,” TOFE meeting paper (2016).

LLNL leads assessment of divertor concepts for advanced systems

- Determine conditions for partial and fully detached divertors obtained by impurity seeding using UEDGE
- Compare peak target-plate heat-fluxes for tilted-plate and flat divertors
- Calculate alpha-particle (helium) removal by pumping in private flux regions
- Provide divertor shapes consistent with other system requirements (space limitations, tritium breeding, etc.)
- Assess impact of charge-exchange sputtering with DEGAS 2

Impurity radiation contours for two possible ACT-1 divertor geometries



Tom Rognlien and Marv Rensink

M.V. Rensink, T.D. Rognlien, *Fusion Sci. Tech.* **67** (2015) 125.

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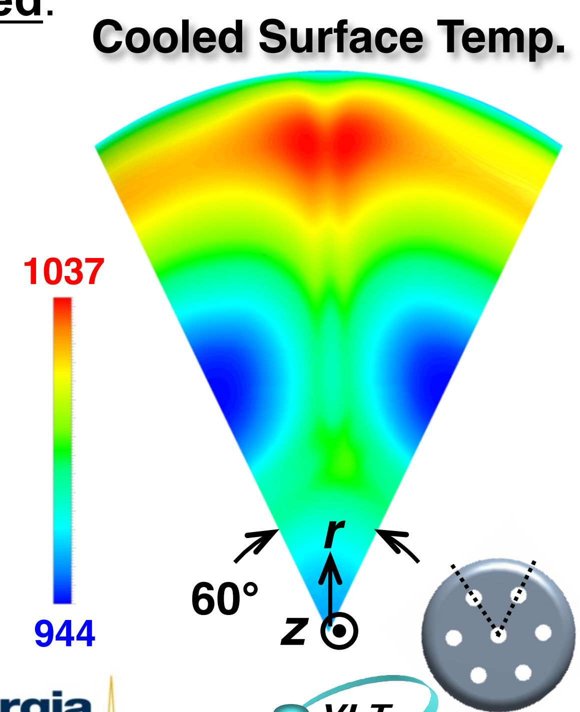
Thermal-Hydraulics Studies of Helium-Cooled Divertors at Georgia Tech

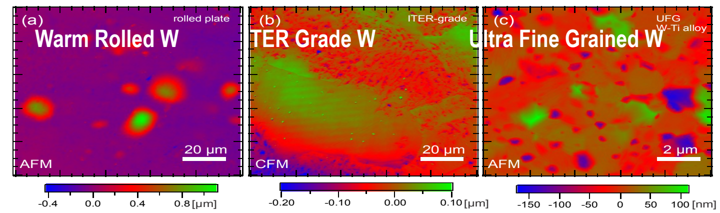
- GT Helium Loop upgraded to inlet temperatures of 400 °C
  - Experiments on HEMJ model at different gaps *H* = 0.5 & 1.5 mm
  - New Inconel X-750 gaskets (courtesy of PHENIX partners)
- Numerical optimization/simulation of HEMJ "variants"
  - **Initial results** => <u>**HEMJ design can be simplified**</u>: 7 jets impinging on flat (*vs*. curved) surface gives higher HTC, reduces pumping power
  - Currently using one-way CFD/FEM coupling
  - Implementing two-way coupling: estimate differential thermal expansion
- Designing larger He loop
  - Mass flow rate $\dot{m}$ ~100 g/s (*vs.* current 10 g/s)
  - Initial simulations (HEMJ) q ~ 7.5 MW/m^2 heat flux feasible with reversed heat flux approach using water jet-impingement cooling



M. Yoda, S. I. Abdel-Khalik, B. Zhao, S. Musa

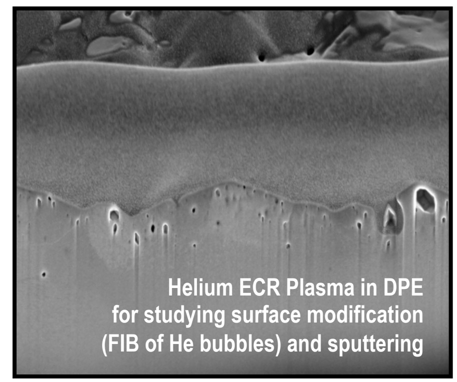
SNL advances the understanding of PMI and PFC design while supporting R&D needs for ITER

- Science based understanding of H/D/T and He in materials with high fluxes (TPE/PISCES collaborations)



Kolasinski, Int. J. Refact. Met. H. 2016; Buchenauer, Fusion Eng. Des. 2016

Dynamic response of surfaces (UT/ PISCES collaborations)



Kolasinski, 2016 DOE Early Career award; Donovan, Phys. Scr. 2016

- Improved measurements of plasma edge and erosion/redeposition (DIII-D/NSTX-U/ EAST collaborations)

DIII-D Lower Divertor Shelf Langmuir Probe Array

Watkins, J. Nucl. Mater. 2015; Wampler, Phys. Scr. 2014

- Science-based engineering: stress, heat transfer and PFC failure modes; novel materials / designs

Nygren, invited oral ISFNT, Phys. Scr. 2016,
invited review (liquid surfaces) Nucl. Mat. Energy 2016; Youchison, Fusion Sci. Technol. 2015

Sandia National Laboratories

VLT Virtual Laboratory for Technology For Fusion Energy Science

Promote an Integral Approach to Handle Mildly Radioactive Fusion Materials

- Fusion generates large quantities of low-level waste
  - Too much for existing LLW sites
  - Not environmentally attractive nor economic solutions.
- Possible approach:
  - Develop new guidelines that allow fusion to generate Greater Than Class C (GTCC) waste.
  - Explore potential avenues that allow revisiting strict compositional boundaries within which fusion materials community is currently working. This means less restrictive guidelines for material selection and development; no restrictions on alloying elements; no need for costly impurity control.
- Promote recycling/clearance of fusion materials. All fusion components can potentially be recycled shortly after decommissioning. US and international industries already demonstrated the economical and technical feasibility of recycling and clearance.
- **Potential game changer**: alloy ODS with Al to improve LM corrosion-resistance; W-Re alloys for divertor structure; Nb impurity > 5 wppm; Ta, Zr, Hf, Nb or Mo as FW and divertor armor; RAFM F82H and Eurofer alloys with Nb > 5 wppm and Mo > 30 wppm (no impurity control).

– L. El-Guebaly **and M. Zucchetti, "Progress and Challenges of Handling Fusion Radioactive Materials," Fusion Sci. Technol., Vol. 68 (2015).**
– **L.A. El-Guebaly and L. Cadwallader, "Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy." Chapter in book: Radioactive Waste: Sources, Management and Health Risks. Susanna Fenton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).**
– L. A. **El-Guebaly, "Future Trend Toward the Ultimate Goal of Radwaste-Free Fusion: Feasibility of Recycling/Clearance, Avoiding Geological Disposal." J. Plasma and Fusion Research, 8, 3404041-1-6 (2013).**

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VLT
Virtual Laboratory for Technology
For Fusion Energy Science

Where are we going?

- Better visibility within the Office of Science and nationally
  - If we are called a lab, we will act like a lab (highlights, white papers, meetings with DOE, etc.)
- Undertake priority analyses
  - From system studies and a technology perspective, what R&D needs to take place, and when, to advance a fusion energy solution
  - Provides a consistent means to prioritize within the program from a scientific perspective
- Better focus for the future
  - Allows the VLT to act as a true collaboration and less like a loose collection of programs